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Flat plate aluminum heat pipe collector with inherently limited stagnation temperature

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Abstract

This paper presents a new flat plate collector technology based on heat pipes. The use of heat pipes can lead to several advantages over direct flow collectors: A simple hydraulic interconnection, an inherently limited stagnation temperature and substitution of copper. This flat plate collector prototype with aluminum heat pipes features all three aspects in one collector. The paper outlines the theoretical modeling approaches and presents the construction of the collector as well as detailed results of measurements of the collector performance. By use of specially designed heat pipes the heat transfer is limited at higher temperatures, which leads to a maximum stagnation temperature of 140°C at the manifold of the collector, thus preventing damages to the solar circuit fluid and solar components. Therefore, cost savings regarding the collector by substituting copper with aluminum and cost savings regarding the solar system due to lowered stagnation temperatures can be achieved.

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Keywords: flat plate collector; heat pipe; stagnation; aluminum; copper substitution

1. Introduction

Heat pipes are commonly used in vacuum tube collectors and may lead to several advantages in comparison to direct flow collectors such as simpler hydraulic interconnection, lower stagnation temperatures and even the substitution of copper. However, commercially available heat pipe solutions for collectors are designed fairly similar

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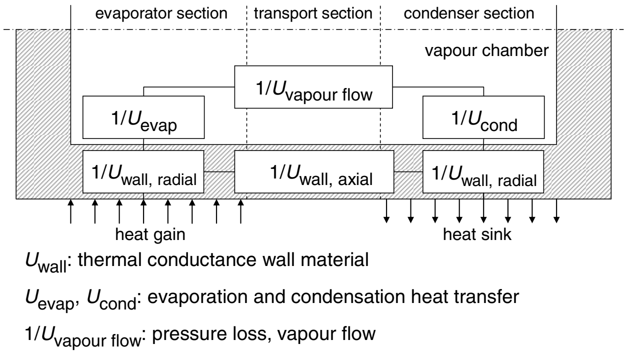
– copper heat pipes with water as working fluid – and the theoretical modeling and optimization is still not thoroughly exploited. On the one hand the paper outlines a newly developed set of theoretical tools for dimensioning and optimization of heat pipes for the use in thermal collectors. On the other hand a new flat plate collector technology with aluminum heat pipes is presented, which highlights all of the beforehand mentioned advantages.

2. Theoretical modeling of heat pipe solutions

Heat pipes represent an additional thermal resistance in the gain heat path of the collector, given that they are positioned between the absorber and the solar circuit. Additionally the thermal connection between heat pipes and solar circuit fluid – the manifold – also represents a thermal resistance. For optimization of heat pipes in vacuum tube collectors or analysis of heat pipe solutions for other types of collectors the heat transfer characteristics of both components have to be known.

On the basis of existing empirical models and experimental data, which are determined at ISFH with novel test rigs (as described e.g. in [12]), we developed a new set of equations to fully describe the heat transfer characteristic of heat pipes. For calculation of the thermal resistance of heat pipes the single heat transfer mechanisms need to be considered. Fig. 1 shows an equivalent resistance network of the main influences on the overall thermal resistance of heat pipes.



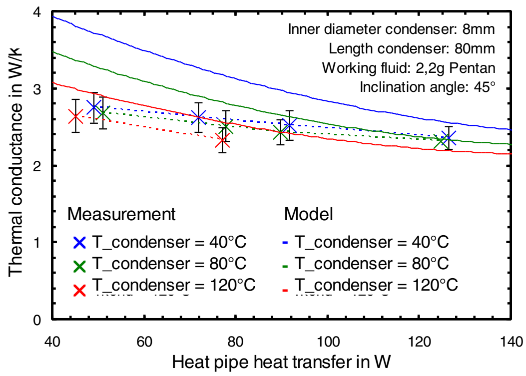


Fig. 1. Equivalent resistance network of the main influences on the overall thermal resistance of heat pipes (right) and exemplary comparison of measured and theoretical modeling of thermal conductance (inverse of thermal resistance) of a heat pipe with Pentan as working fluid (left)

The pressure loss of the vapor flow and the axial heat transfer due to thermal conduction in the heat pipe wall can be neglected since these influences are very small. The radial conduction in the tube wall at the evaporator and condenser of the heat pipe can be calculated by the standard approach for thermal conduction in a hollow cylinder (e.g. [10]). The heat transfer by evaporation and condensation inside heat pipes have been the subject of many publications as for example [1,2,3]. Comparison to own measurements of the thermal resistance of heat pipes for collectors at ISFH shows, that the calculation of the evaporation and condensation heat transfer coefficients in [1] shows the best agreement. [1] is therefore used in our heat pipe model according to Fig. 1.

Regarding heat pipes – besides the thermal resistance – the heat transfer limitations have to be taken into account, too. We found, that for the use of heat pipes in solar collectors only the entrainment limitation and the dry out limitation have to be taken into consideration. Fig. 2 shows, that the entrainment limit occurs at lower operation temperatures. Therefore, the heat pipe has to be designed, so that the entrainment limit does not affect the collector's performance. Fig. 2 shows also, that the dry out limit can be used for lowering stagnation temperature since it occurs at higher operation temperatures.

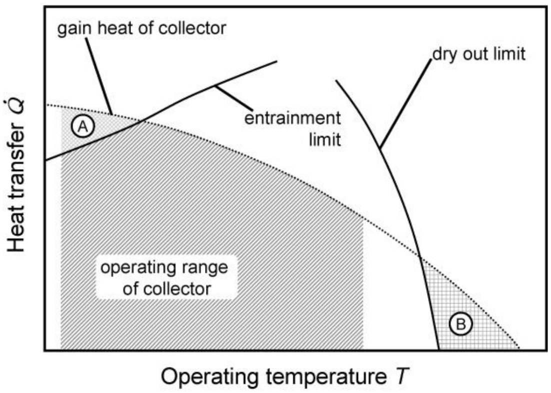


Fig. 2. Schematic comparison of gain heat of collector per heat pipe and heat pipe's heat transfer limitations. Area A resembles the case, that the heat transfer limitation is lower than the collector's gain heat which would reduce the collector performance at lower temperatures. Area B illustrates the case for a decrease of the stagnation temperature of the solar circuit fluid due to heat transfer limitation

Regarding the entrainment limitation measurements at ISFH and evaluation of published theoretical models show, that [4] is accurate and allows dimensioning in this regard. The main influence on entrainment is the diameter of the heat pipe as shown in Fig. 3 (left). The dry out limit was also evaluated experimentally at ISFH. It was found, that no published model describes the dry out limit of heat pipes for collectors correctly due to their special geometry. A new model was developed, which shows good agreement to measured data [5]. The main influences on the dry out limitation are type and amount of working fluid as shown in Fig. 3 (right). Therefore, we have developed a set of tools, which allows the dimensioning of heat pipes for integration in a new flat plate collector prototype.

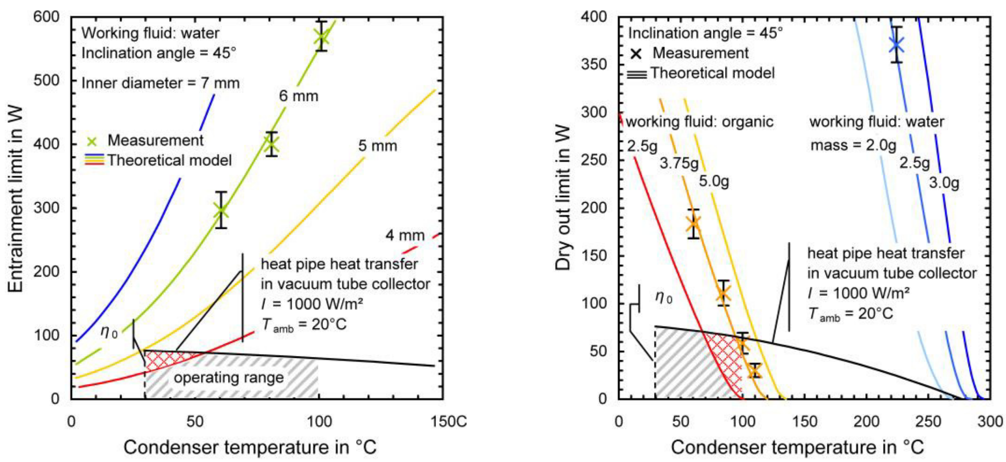


Fig. 3. Comparison of experimental results with theoretical model of the entrainment limit and variation of heat pipe inner diameter and corresponding influence on the collector performance (left) and comparison of experimental results with developed model of the dry out limit and possible decrease of the stagnation temperature in the solar circuit through the use of organic working fluids in the heat pipe (right)

To calculate the thermal resistance of the manifold the simulation tool Ansys CFD was used. The simulations were also carried out for manifolds of vacuum tube collectors. These simulations have been validated with measured data, which was gained with a newly developed test rig. Fig. 4 shows an exemplary simulation geometry of a standard manifold for ETCs with calculated fluid flow and temperature distribution on the left side and the comparison between measurement and modeling of the thermal conductance on the right side. Within the simulation several design concepts for the manifold for integration in a flat plate collector were investigated. It was found that the needed heat transfer capabilities could be reached with a reasonable usage of material. Optimizations regarding the connection of the heat pipes to the manifold and material usage where carried out, which lead to a suitable manifold configuration, which was implemented.

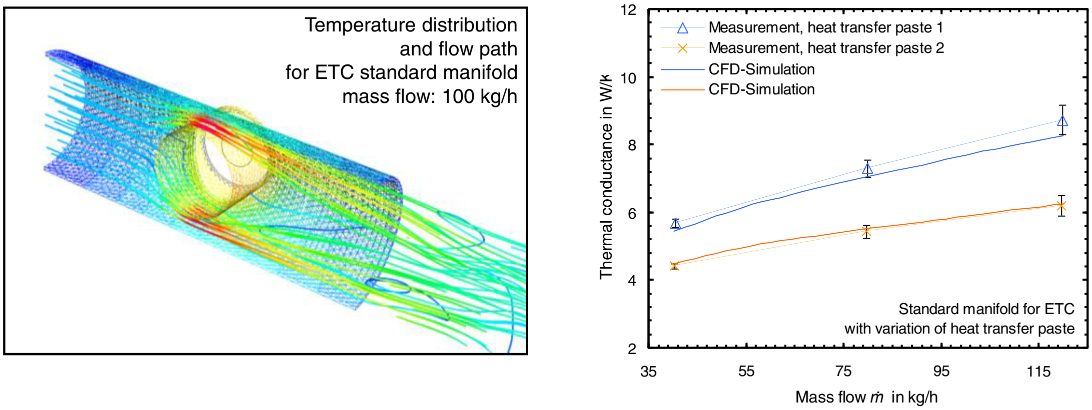


Fig. 4. Temperature distribution and flow path for ETC standard manifold (left) and comparison of measurement and theoretical modelling with CFD-Simulation with variation of heat transfer paste (right)

3. Development of aluminum heat pipes

The substitution of copper with other less expensive materials like aluminum for the use as heat pipes tubes can lead to lower manufacturing costs. Compared to direct flow collectors the corrosion risk of the aluminium tubes is avoided, since the heat pipes are not in contact with the solar circuit fluid. Table 1 shows a comparison of flat plate absorber material costs. Typical direct flow absorbers with copper tubes and aluminum absorber plates are compared to possible heat pipe absorber configurations with aluminum heat pipes (including copper manifold). The calculation attests that a material cost reduction can be possible and is significant if standard aluminum alloys are used. (In Table 1 alloy 1 is a standard aluminium product and alloy 2 is an aluminium tubing specially designed for the use in solar collectors).

Table 1. Comparison of absorber material costs, 1.75m² absorber area, 0.5 mm aluminum absorber plate, material costs: exchange market prices plus processing costs (approximated), V1 and V2 are heat pipe configurations developed at ISFH

Type	Absorber material costs in €	Comment
Harp	25.70	Typical copper tubing (average costs)
Meander	31.50	Typical copper tubing (average costs)
V1	31.20	copper heat pipes
V2 - Standard	20.50	aluminum heat pipes (alloy 1, standard)
V2 - Special	22.10	aluminum heat pipes (alloy 2)

Aluminum heat pipes have not been used in solar thermal collectors yet, but literature shows that they have already been broadly investigated [6,7,8,9,10,11]. Overall the use of water in aluminum heat pipes is not recommended due to corrosion problems. Otherwise, the use of organic fluids seems to be possible. The aim of our work was to determine, if aluminum heat pipes with organic fluids are suitable for the use in solar thermal collectors. Therefore aluminum heat pipes were produced and tested regarding their durability and thermal heat transfer capabilities. At ISFH we have developed a filing rig for the assembly of heat pipes, which was used for the production of the aluminum heat pipes. The standard steps for the production of heat pipes are cleaning, evacuating, filling and closing the heat pipe.

The durability of aluminum heat pipes with organic fluids was tested by thermal aging tests. The tests were carried out in an oven with a length of 2 m wherefore long heat pipe samples can also be investigated. The rating is based on the starting temperature difference. The measurement of the starting temperature difference is carried out in a rapid test, which was developed at ISFH. The starting temperature difference is the temperature difference between evaporator and condenser of the heat pipe, at which the heat pipe starts to operate. With lower temperature differences the heat pipe does not transport any heat. The starting temperature difference depends on the amount of inert gases inside the heat pipe. Inert gases do not condense inside the heat pipe and therefore block parts of the condenser. A heat pipe with a starting temperature difference of zero is therefore optimal and has no inert gases.

Several thermal aging tests were carried out. In the following an exemplary aging test is presented. Fig. 5 shows the starting temperature differences after thermal aging. It could be shown, that up to a temperature level of 215°C and 200 hours of temperature exposure, no signs of inert gases inside the heat pipe could be detected. Above a temperature of 230°C the starting temperature difference increased drastically, which attests a defect of the heat pipe specimens.

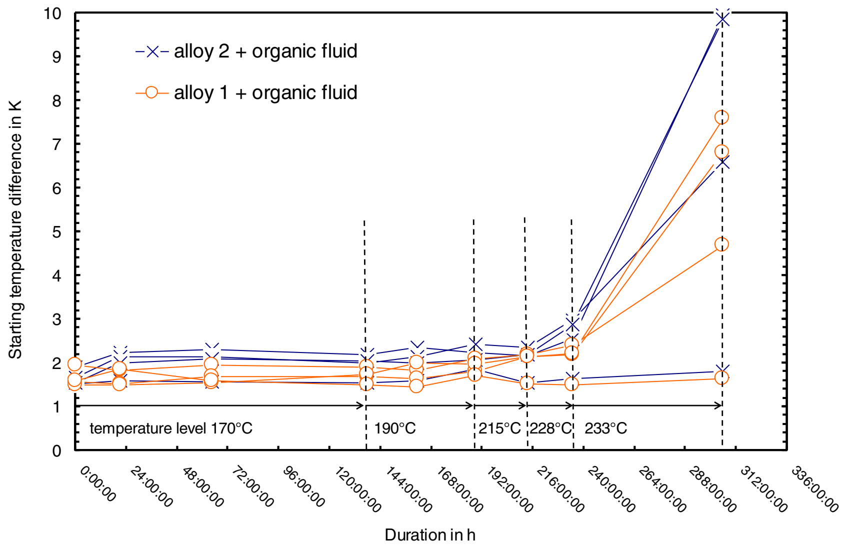


Fig. 5. Starting temperature difference of aluminum heat pipe specimens during thermal aging tests as an indicator for degradation of heat pipes

The higher starting temperature difference occurring at high temperatures can indicate the presence of leakage or inert gas formation by chemical reaction. Regarding chemical reactions including corrosion, a visual inspection of the state of the inner wall surface and the working fluid was carried out. As a result, no changing of the wall surface state over the time of the exposure was reported. This implies that the high starting temperatures differences, which occurred during high temperature exposures, are due to leakage of the tube. Due to the high pressure inside the heat pipe at higher temperatures the aluminum tubes deformed at the area of brazing, which led to leakage. This means, that the only problem regarding the investigated aluminum heat pipes is the mechanical load, which occurs during operation due to high pressure. These deformations do not occur, when the heat pipes are being used in flat plate collectors, since the mean temperature of the heat pipes during stagnation (about 170-180°C) and therefore the pressure inside the heat pipe is lower than at the critical temperature of 215°C. The tested specimens therefore are suitable for the integration in flat plate collectors. For vacuum tube collectors a thicker wall or optimized closing procedures would have to be implemented.

4. Flat plate collector with heat pipes

Heat pipes with water as the working fluid and a good thermal connection of the condenser to the solar circuit (manifold) as used in vacuum tube collectors can achieve high values of collector efficiency factor F'. This approach can be transferred to flat plate collectors without system adjustment. For reduction of stagnation temperature – using the dry out limitation of heat pipes with organic working fluids – the following aspect has to be taken into account: The thermal resistance of heat pipes with organic working fluids is higher than of heat pipes with water and also the thermal losses of a flat plate collector are larger than in vacuum tube collectors. This causes a low collector efficiency factor F' and after all a low collector efficiency. Thus, low thermal resistances of the heat pipes despite the use of organic working fluids and a low thermal resistance of the manifold have to be achieved.

By means of the beforehand mentioned theoretical modeling approaches of heat pipes and manifolds, we investigated the possibility to integrate heat pipe solutions with organic working fluids in flat plate collectors. We identified novel organic working fluids with better material properties and also developed optimized heat pipe geometries. For flat plate collectors the degrees of freedom regarding design of the manifold are higher because the assembly of heat pipes and manifold of the collector are carried out in production and not on the roof by the installer. Therefore, various constructive approaches have been evaluated. As a result, we have designed a collector configuration with a minimized use of material. Subsequently, we have constructed a prototype flat plate collector, where the framing and glazing correspond to commercially available solutions. The transmittance of the glass cover was 90% ± 1%, the absorptance of the absorber 95% ± 2% and the thickness of the backside insulation 50 mm. The new absorber-heat-pipe-manifold solution was implemented in cooperation with our project partner. The system is based on the classic semi-finished parts tube and metal sheet with low machining complexity. Fig. 6 shows the flat plate collector prototype. The area of the manifold is provided with insulation, and thus is outside the radiation absorbing surface in order to ensure a thermal decoupling between the solar absorber and the solar circuit fluid in case of stagnation. The heat pipes of the prototype are made of aluminum.

Fig. 6. Flat plate collector prototype with aluminum heat pipes. The solar circuit fluid only flows through the manifold, which is located at the top of the collector and is not part of the absorbing surface. Standard flat plate collector framing, transmittance of glass cover: ~90%, absorptance of absorber: ~95%, thickness of backside insulation: 50 mm

The flat plate collector prototype was measured in the solar simulator at ISFH with an irradiation of about 900 W/m² and ambient temperature of about 25°C. For determination of the conversion factor both collector inclination angle and mass flow where varied. The conversion factor as a function of tilt angle and mass flow rate ranged from 0.68 to 0.76. An adaptation of the geometry of the heat pipes and an improvement of the heat transfer of the manifold are topics of further investigations to increase collector efficiency. It is assumed, that without the increase of material conversion factors of 0.75 and above at standard conditions (inclination angle 45°, and flow rate 120 kg/h) can be achieved.

Besides the experimental determination of the conversion factor, the collector efficiency curve was recorded also. For this purpose, a high temperature thermostat was used, and several temperature sensors where positioned inside the prototype to evaluate the collector performance and stagnation behavior above a fluid temperature of 100°C. Fig. 7 shows an exemplary collector efficiency curve with cut-off at higher temperatures due to the dry out limitation of the heat pipes.

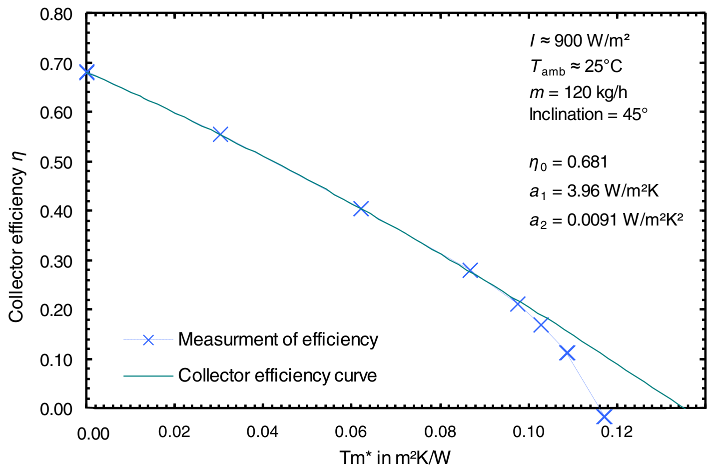


Fig. 7. Collector efficiency curve of the flat plate collector prototype with cut-off at higher fluid temperatures

The thermal losses of the prototype with heat pipes are typical for a standard flat plate collector. The collector efficiency is zero at a fluid temperature of about 130°C. The influence of the heat pipe's dry out limitation on the collector efficiency starts at about 115°C fluid temperature outside the typical operating range, and therefore does not affect the collector performance. During stagnation the temperature distribution inside the collector – especially at the solar circuit fluid – is highly affected, though. Fig. 8 shows the temperature profile of an exemplary heat pipe in the collector. It can be seen that a typical temperature distribution of flat plate collectors in the case of stagnation exists in the region of the absorber with a maximum temperature of about 170°C. The manifold and therefore the solar circuit fluid remain at a temperature level of about 130°C. This shows a decrease of maximum temperature load on the solar circuit fluid of 40 K compared to direct flow flat plate collectors in case of stagnation.

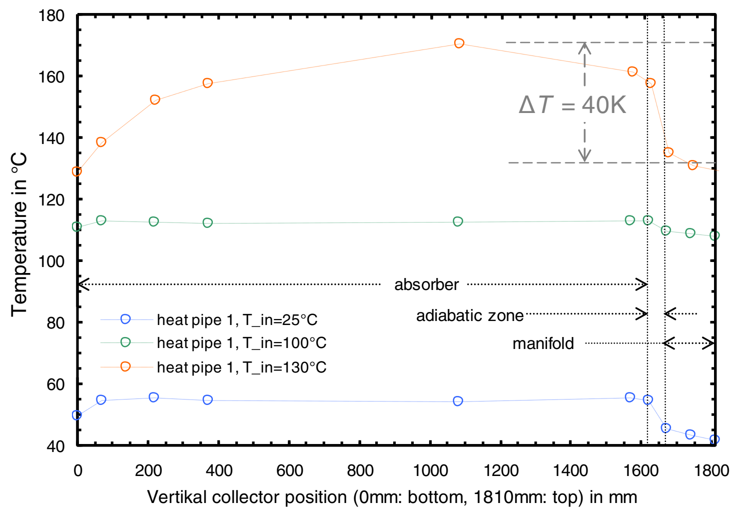


Fig. 8. Vertical temperature distribution inside the collector along one heat pipe in the middle of the collector, (Heat pipe equipped with several temperature sensors), Temperature distribution for operating conditions with solar fluid inlet temperature of 25°C and 100°C and at stagnation with fluid inlet (equal to outlet) temperature of 130°C

In addition, the stagnation temperatures were determined experimentally for further boundary conditions (but also with collector heat gain and efficiency equal zero). In the first case the fluid circuit is still connected but without flow and the wind velocity is zero (resembles real stagnation in plant operation); in the second case the fluid circuit is disconnected and the wind velocity is also zero (dry stagnation). Table 2 illustrates the results.

Table 2. Maximum absorber and solar circuit temperatures for three different measuring methods of collector's stagnation behavior at Irradiation of 900 W/m² and ambient temperature of 25°C

	Solar circuit, flow through, wind	Solar circuit, no flow, no wind	Dry stagnation (no circuit, no wind)
$T_{absorber,\,max}$ in °C	171.3	178.9	188.4
$T_{manifold,max}$ in °C	131.6	138.3	142.1

It turns out that with an irradiation of about 900 W/m² and an ambient temperature of 25°C for stagnation in accordance with the plant operation a maximum temperature at the fluid in the collector circuit (manifold) of 138°C is reported. The maximum absorber temperature in this case is at 179°C, though. At elevated irradiation of 1000 W/m² and an ambient temperature of 30°C the maximum temperature at the absorber is expected with about 200°C. Due to the thermal decoupling through the heat pipes, the temperature at the manifold will increase only slightly. This means, that with this flat plate collector prototype, a reduction of the maximum stagnation temperature of the solar circuit fluid from at least 40K to about 140°C is achieved. A limitation of the maximum temperature at the manifold to even lower values may be possible through heat pipe optimization.

Thus, this flat plate collector prototype inherently limits the stagnation temperature of the solar fluid. Therefore it leads to less thermal degradation of the solar circuit fluid and can even prevent steam generation at all, if the system pressure is raised slightly. This function of the collector is achieved with aluminum heat pipes with an organic working fluid, which also enables a material cost reduction of the absorber configuration.

5. Conclusion

The newly developed modeling tools for heat pipes and manifolds allow evaluation of heat pipe solutions for vacuum tube and other types of collectors. In this paper we used them to design heat pipes for the integration in a flat plate collector. The presented prototype exhibits a new collector technology with aluminum heat pipes minimizing the use of copper. At the same time a lower stagnation temperature was achieved as a result of the thermal decoupling of absorber surface and solar circuit fluid and the implementation of organic fluids. A maximum stagnation temperature of 140°C was measured at the manifold, whereas the absorber plate reaches typical stagnation temperatures.

With this kind of collector a simpler hydraulic interconnection of the collector array without problems of non-uniform flow, a longer lifetime of the solar fluid, a smaller expansion vessel and overall less expensive components inside the solar loop due to lower stagnation temperatures can be achieved. Furthermore the substitution of copper with aluminum can decrease the collector costs. The complexity of solar thermal technology is thus transferred from the system to the collector. This new approach can lead to simpler, more reliable and thus lower priced solar thermal systems.

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